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Remreed Switching Networks for No. 1 and No. 1A ESS:

Development of a Remanent Reed Sealed Contact

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The development of the remreed sealed contact is described with emphasis on the various problems that had to be solved to get a viable manufactured product. The necessary characteristics of the switchable reed material and the unique features of the material processing and contact processing steps are discussed. Details are then presented of the selection of hard gold as a contact material and the problems encountered in its application by electroplating. The contact assembly operation is described, and the difficulties encountered at this stage are elaborated on. Finally, the physical design and testing of the contact are discussed, along with the interactions among contact geometry material properties, processing steps, test parameters, and performance.

I. INTRODUCTION

The largest use for dry reed sealed contacts in the Bell System is for matrix switches of various types used in the network of the No. 1 Electronic Switching System (No. 1 ESS). To achieve the pulse actuation feature required in these arrays, switchable semihard magnetic plates are associated with the contacts at each point in the matrix.[1] It has been obvious for many years that it might be advantageous to make the reeds themselves out of the semihard magnetic material and eliminate the plates. Such a self-latching or remanent reed contact was first proposed by R. L. Peek in the late 1950s. Further development was carried out in the early 1960s using an iron-cobalt-vanadium alloy called Remendur as the magnetic material. Serious difficulties were encountered in a number of areas, while at the same time the soft reed matrix known as the ferreed switch was proving highly successful. The three most serious problem areas were reed stamping, electrodeposition of a contact material, and sealing.

To develop the desirable magnetic properties of Remendur, a high degree of cold work is necessary. This was accomplished by cold-drawing the wire to the required diameter. When reeds were stamped out of this highly cold worked material, they tended to split and crack, and tool life was extremely short. When sealed contacts were made and tested, many were found to have large leaks because the surface of the drawn wire was rough. Difficulties were also encountered in obtaining adherent electrodeposited films of contact material on the Remendur.

In 1969, interest in remanent reed contacts (commonly referred to as remreed contacts) was revived when they were considered for the No. 4 ESS toll network. However, at that time a two-piece reed design was considered to avoid the problems previously encountered. The idea was not pursued when estimates of development time indicated that such a project would not fit the No. 4 ESS development schedule, although a small effort did continue on development of a remreed contact with a monolithic reed structure.

By late 1970, the basic problems associated with a monolithic structure appeared to be solved. The reed-forming difficulties were overcome by demonstrating that the stamping operation itself introduced sufficient cold work into the material so that annealed wire could be used. The sealing problem that was related to surface defects in the wire was solved by improvements in wire processing. Poor adhesion of the contact material was solved by development of effective electrochemical cleaning procedures.

Meanwhile, serious interest was developing for a cost and size reduction of the network for No. 1 ESS. Paper studies of the design of remreed matrix switches and networks indicated that a size reduction of 4 to 1 in the trunk frames could be achieved along with substantial cost reduction. Early in 1971, the decision was made to go ahead with full-scale development of a remreed contact and an associated remreed network for No. 1 ESS. The remreed contact was subsequently coded as the 238A contact.

II. MAGNETIC MATERIAL

Rather than immediately pursuing the use of Remendur based on these early successes, it was decided to first review other magnetic materials. Only those commercially available were considered because of the very tight development schedule adopted for the project.

It was the unusual combination of required characteristics that made it difficult to provide a magnetic material suitable for use in the 238A sealed contact. To avoid a glass development program, the material should have thermal expansivity properties closely matching

that of the glass used in the manufacture of the 237-type soft reed contact. It must act as a permanent magnet whose magnetic strength (or flux) is high and whose coercive force is within prescribed limits dictated by switch design parameters such as dimensions, operate-and-release current requirements, contact pressure limitations, etc. Furthermore, these magnetic properties should not be deleteriously affected by the heating associated with the glass-sealing operation. The material must also be ductile enough to permit commercial fabrication into wire and subsequent stamping into reed members. Finally, the material must be amenable to processing in a manner which would yield wire having a very-high-quality, defect-free surface to ensure hermetic sealing to the glass.

The new survey of available magnetic materials led again to tbe selection of "Remendur-type alloys" as offering the best potential for meeting the diverse requirements. These alloys contain approximately 49 percent cobalt, 2 to 5 percent vanadium, and the balance iron. In these alloys, it is possible to control the coercive force by varying the vanadium content, provided that the material is adequately cold-worked and given a final 2-hour heat treatment at 600°C. A good rule-of-thumh approximation is that the maximum coercive force ohtainable is equivalent to 10 times the vanadium content, expressed in weight percent. A variety of alloys, types 33, 38, and 48, have been used in switching applications, the numerical designation reflecting the desired coercive force obtainable from alloys containing 3.3, 3.8, and 4.8 percent vanadium, respectively. The residual induction for these alloys is above 16,000 gauss.

Initial design concepts for the 238A contact involving factors such as reed dimensions, gap hetween reeds, pulse current for operate and release, etc., indicated that the flattened portion of the reed memher would have to have a coercive force of 27 $\pm$ 3 oersteds and a minimum remanence of 15,000 gauss. In keeping with past Remendur nomenclature, the new required alloy was tentatively designated as type 27 Remendur.

The thermal coefficient of expansion for Remendur was found to be 10.3×10^{-6} per °C over a temperature range of 30 to 500°C. This is very close to the 10.2×10^{-6} value for the 52 alloy (51 percent nickel—49 percent iron) used in the 237B sealed contact, and therefore no expansivity prohlems were anticipated in the glass-sealing operations. This was later suhstantiated in laboratory sealing tests, which are discussed in more detail in Section IV.

Thus, it became apparent that a Remendur alloy containing 2.7 percent vanadium would meet the magnetic and expansivity requirements for use in the 238A sealed contact. The remaining problems,

therefore, were whether the material could be processed to yield wire ductile enough for reed stamping, smooth enough to ensure hermetic glass sealing, and stable enough to resist degradation of magnetic properties due to heating during the sealing operation.

Softening of Remendur alloys is usually accomplished by heat treatment at 900 to 950°C followed by a drastic quench in ice brine. However, this procedure was found to be unsuitable for annealing the desired 0.53-mm diameter wire due to difficulties associated with quenching large coils of wire and because an adherent abrasive oxide scale was formed on the wire that would cause excessive die wear in the stamping operations. Experiments with short-time heat treatments resulted in the development of a strand-annealing process that produced wire having satisfactory ductility. The process consisted of pulling wire under a hydrogen atmosphere at a rate of 6 feet per minute through a 6-ft long furnace controlled at 950°C. After heating, the wire passed through a water-cooled chamber at the exit end of the furnace which rapidly cooled it to room temperature before it emerged into the air and was taken up on a spool. This strand-annealing process produced wire with a bright surface finish having a tensile strength of 1.31×10^9 N/m² and an elongation of 12 percent (in a 25.4-cm gauge length). Stamping tests showed that such wire could readily be formed into reed members with no excessive die wear.

Since reeds stamped from soft wire represent a composite structure consisting of annealed material in the shank and cold worked material in the paddle, it was apparent that the magnetic characteristics of the shank and paddle sections would be different. The magnitude of this difference was determined from measurements on specimens of 0.53-mm diameter wire and 0.18-mm thick tape flattened from the wire, after each were given a final 2-hour heat treatment at 600°C. The effect of strand-annealing temperature on the magnetic properties of heat-treated wire and tape is illustrated in Fig. 1. For the wire, there is a pronounced drop in coercive force starting above 700°C, reaching a minimum at 800 to 850°C, then rising to a maximum at 950°C and declining above 950°C. The residual induction or remanence drops with increasing temperatures with a leveling out at 850 to 950°C followed by a further decline. Interestingly enough, the amount of cold deformation induced by flattening is enough to increase the coercive force and remanence substantially, and the level of values reached remains relatively constant irrespective of the strand-annealing temperature. Other studies revealed that the magnetic properties of the tape are independent of the degree of flattening over the range in thickness from 0.14 to 0.23 mm. An analysis of the metallurgical phase changes responsible for the magnetic property behavior associated

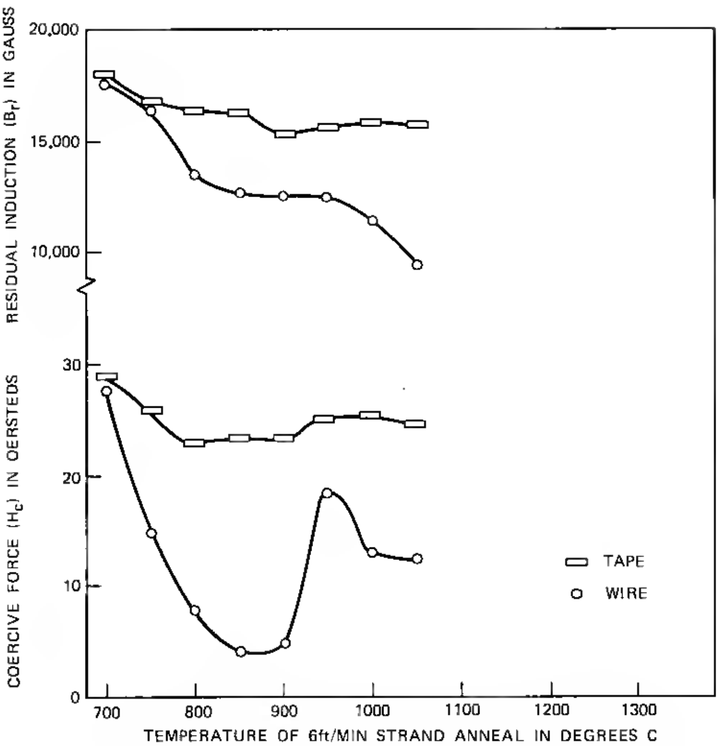


Fig. 1—Effect of strand-annealed temperature on heat-treated wire and tape.

with the strand-annealing process have been described in an earlier article in this journal.[2]

The data clearly showed that the desired minimum difference between properties of wire and tape would be obtainable by strand-annealing at 950°C and that good temperature control would be essential to ensure uniformity of properties. Subsequent data obtained on larger quantities of commercial wire and on sealed-contact switching performance enabled the establishment of tentative magnetic specifications for wire and tape which are given in Table I.

Magnetic tests and microscopic studies on type-27 Remendur reeds removed from sealed contacts revealed that fairly large changes in properties and structure were being produced in about one-half the length of the shank by the glass-seal heating.[3] It was also found that the effects of this heating did not extend into the paddle section, and that there were no changes observed in this portion of the reed. Since the contact characteristics are much more sensitive to the paddle properties, the overall effect of the shank changes were relatively small

Table I — Physical and electrical characteristics of 238A contacts

I. CONTACT REQUIREMENTS

(Coil used for actuation is defined by Fig. 11.)

A. Contact Sensitivity
   1. Release NI—20 to 37.
   2. Operate NI—92 to 127.

B. Flux Ratio: Remanent Flux/Release Flux—1.2 to 1.9.

C. Contact Resistance

   (The resistance is measured between two points 34.54 mm apart on the 238A leads.)
   1. Static test: the contact resistance should be less than 90 mΩ after a 250 NI soak field.
   2. Dynamic test: the contact resistance should not exceed 150 mΩ for more than 1 μs during a 5-ms interval beginning 5.5 ms after a pulse sequence of $-150\ NI$, $+40\ NI$, $+150\ NI$.

D. Contact Ceometry
   1. Overall length—38.05 ± 0.13 mm.
   2. Lead length—greater than 4.45 mm external to glass.
   3. Outside diameter—2.80 mm max.
   4. Concentricity—when rotated about the center line of the glass, all points on the surface of the external lead shall meet the following requirement: One external lead may fall within 1.78-mm diameter circle provided the other lead falls within a 1.52-mm diameter circle.

E. Reed Geometry
   1. Overall length—19.3 ± 0.05 mm.
   2. Paddle length—10.54 ± 0.13 mm.
   3. Paddle thickness—0.185 ± 0.008 mm.

F. Voltage Breakdown: The contacts shall not break down when 800 V dc or 610 V ac, 60 Hz is applied to the terminals.

II. DESIGN PARAMETERS

A. Contact Ceometry

   Contact gap—0.11 to 0.17 mm.

   Contact overlap—0.46 to 0.71 mm.

B. Contact Force: 1.3 to 5 grams.

III. PERFORMANCE CHARACTERISTICS

A. Release Time

   <200 μs for a 4-A, 1-ms release pulse in a remreed crosspoint.

   <500 μs for a standard 4-A remreed control pulse.

B. Chatter Time: <3 ms for a standard 4-A remreed control pulse from a static open condition.

IV. MAGNETIC MATERIAL REQUIREMENTS: The magnetic properties of the Remendur shall be measured on the strand-annealed 0.53-mm round wire and on sections of wire that have been roll flattened to 0.19 ± 0.01 mm thick. In both cases, the samples shall be heat treated for $2\frac{1}{2}$ hours at 615°C ± 5°C. The measurements shall he made on samples that are 203.2 mm long. Samples should be driven into saturation with a uniform field of 100 Oe ± 2 Oe.

A. Round Wire

   Coercive force, H_c to 18 to 28 Oe.

   Remanent flux, 29 maxwells min.

   Squareness, no requirement.

B. Flattened Sections

   Coercive force, H_c—25 to 31 Oe.

   Remanent flux, ϕ_r—36 maxwells min.

   Squareness, B_r/B_{100}—0.85 min. (B_{100} in the flux density measured at 100 Oe.)

and did not have a serious effect on switching performance of the sealed contact.

Wire with a near-perfect surface finish is required to ensure obtaining hermetic seals to the glass. Longitudinal striations as shallow as 3 μm (Fig. 2) provide enough of a path to cause leaks.[4] While commercial procedures had been developed for producing such wire from the 52 alloy used in the 237B contact, new or modified techniques would be required for the Remendur alloy since it was inherently much harder and more difficult to draw. Another complicating factor was that hot rolled Remendur rod is brittle and cannot be drawn unless it is annealed by reheating to 925°C and quenching in ice brine. This heating increases the thickness of the oxide scale on the rod. In addition, long-time heating can cause severe intergranular oxidation,[4] as shown in Fig. 3. Another major source of surface defects results from the processing of billet material into 6.35-mm diameter rod by hot rolling in air at 1200°C. Some surface irregularities are produced by oxide scale chips or other contaminants being rolled into the rod, or by imperfections in the rolls. However, by far the most serious defects are the longitudinal seams caused by fold-overs and laps resulting from the rolling in of corners and fins when the material is being continuously hot-rolled into the variety of cross-sectional configurations necessary to produce rod. The nature of these seams is illustrated in Fig. 4. Figure 5 is a cross section showing the depth of the seams.

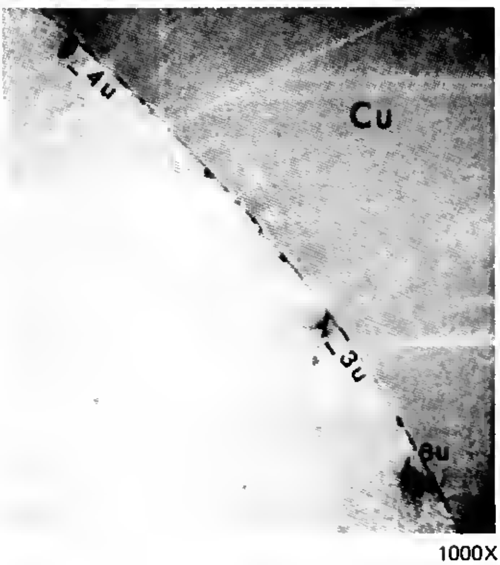


Fig. 2—SEM cross section of 0.53-mm wire showing surface defects.

2000X

REGIONS OF VARYING COMPOSITION

A–BULK REMENDUR
B–SURFACE OXIOE
C–INTERGRANULAR OXIOE
O–ENVELOPEO GRAINS

4X

Fig. 4—Rod surface seam defects in 0.64-cm diameter Remendur rod.

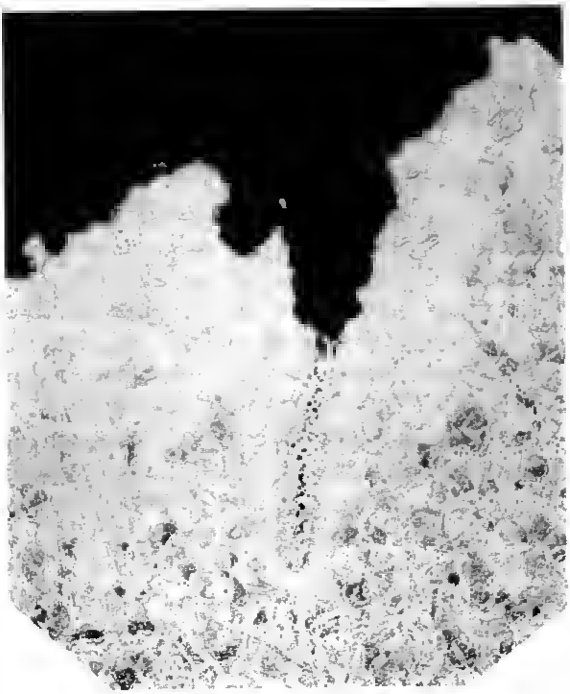


Fig. 5—Cross section of 0.64-cm diameter Remendur rod showing seam defect.

Note that penetration of oxide exists below the hottom of the seam. Unless all this oxide defect is removed, seams will persist through wire drawing, and their presence in finished wire will give rise to leaky seals. Defects of this type and the oxide scale produced hy annealing was removed by shaving and surface grinding a 0.51-mm thick layer from the rod. The resulting surface must be smooth and free of oxides or other hard contaminants. It was found that it was possible to produce Remendur wire with the desired surface finish by the rod conditioning indicated above and careful wire-drawing procedures, such as use of smooth dies, monitoring of die conditions, clean lubricants, etc. Cooperative efforts with Western Electric personnel, to translate lahoratory processing procedures to commercial manufacture resulted in estahlishment of viable sources of satisfactory Remendur wire from outside suppliers.

III. CONTACT MATERIAL

Use of a diffused contact material similar to that employed in other Bell System sealed contacts was precluded by the fact that the mag-

netic anneal of Remendur is carried out at 600°C, and heating to the higher temperatures required for the diffusion of the contact material destroys the desirable magnetic properties of the Remendur reed.

The circuit conditions that the network contacts must withstand are relatively mild. They open and close dry except for cable discharge on make, mostly at voltages below 26 volts. Over the past 10 years life tests have been run under these conditions on soft reed contacts employing nondiffused electroplated contact materials. These tests have included many types of hard gold and all the members of the platinum group. Under these particular circuit conditions, there was very little difference in performance among these materials with respect to development of high resistance due to wear-through of the precious metal layer. There were, however, differences among these nondiffused materials and between any of them and our standard diffused gold-silver surface, used on the 237B, with respect to sticking, and with respect to the incidence of very early high-resistance failures due to contamination, particularly by organics.

The platinum group metals were essentially free from sticking but in general suffered from organic contamination problems. The hard golds also had some organic contamination problems, although not as severe as the platinum group metals. With respect to sticking, the hard golds were about equivalent to the diffused gold-silver surfaces of the 237B.

Hard gold was finally selected for use on the 238A contact for the following reasons:

- (*i*) Under the network circuit conditions, it is nearly as good as any of the platinum group metals with respect to wear-out.
- (*ii*) It is less susceptible to organic contamination problems.
- (*iii*) Western Electric and Bell Laboratories have had extensive experience with hard gold plating.
- (*iv*) The greater tendency toward sticking on hard gold compared to the platinum group metals is only a relative evaluation. In an absolute sense, the performance of hard gold below 5×10^6 operations is equivalent to diffused gold-silver which has proven acceptable in the ferreed switch used in the No. 1 ESS network.

Some difficulty was experienced initially in obtaining good adhesion of the plated hard gold layer to the Remendur. This was overcome by an anodic pretreatment step in an alkaline solution.

Stalica has shown by auger analysis that the critical factor in obtaining good adhesion and blister-free deposits is the removal of vanadium (in the form of both oxides and nitrides) from the surface.[5]

Eisenmann has shown that the anodic pretreatment step accomplishes this and that essentially any alkaline agent will suffice.[5] Sodium hydroxide, trisodium phosphate, or potassium cyanide have heen used with equal effectiveness, although potassium cyanide is now used in production.

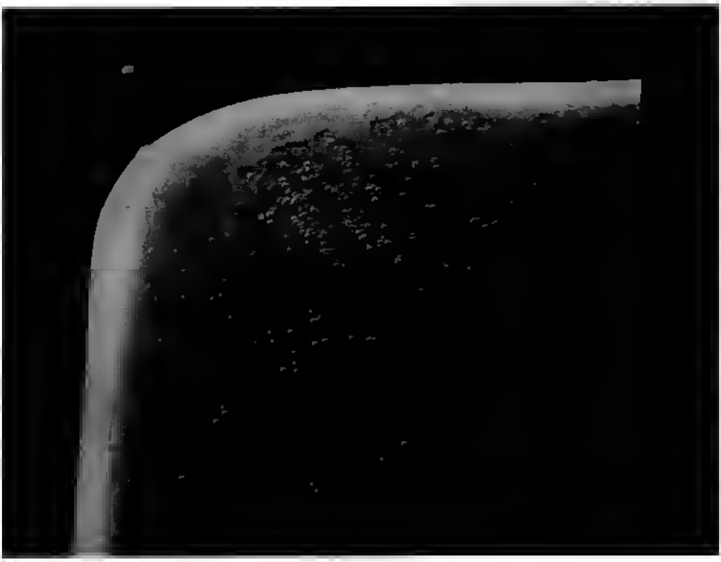
One serious prohlem associated with plating was encountered in early production of the 238A contact. This was the inahility to ohtain smooth deposits on the Remendur surface using production equipment. The deposits were highly nodular. Figure 6a is a typical example of the type of deposit ohtained. The cause of the nodular plate was found to he magnetic particles on the reed surface. Figure 7 is a cross section of a nodule. Every nodule has heen found to have a particle at its center. Electron prohe analysis shows the particles to he magnetic material. The prohlem was enhanced hy the fact that the production plating facility employed a magnet to hold the reeds against an electrical contact plate. This had two effects. First, it caused the reeds to act like magnetic hrooms, picking up any magnetic particles in the haths associated with the plating process. Second, and much more important, it caused any magnetic particles on the reed surface to stand up like the quills of a porcupine with their long axis aligned with the magnetic field.

The final solution to the nodule prohlem involved installation of 1-μm filters on all haths in the plating process, hetter demagnetization, improved cleaning procedures for the reeds prior to plating, and design of a nonmagnetic plating rack. Figure 6h shows a typical plated surface after introduction of the ahove modifications in the process.

IV. GLASS–TO–METAL SEALS

As previously indicated, one reason for selection of Remendur was the close match of its coefficient of expansion with that of the availahle glass used for the 237-type contact. The thermal expansion curves for both Remendur and the 52 alloy sealing glass are shown in Fig. 8. The slight mismatch in the coefficients is in the direction to put the glass-to-metal seal under slight radial compression. This is intentional and is intended to increase the strength of the seal under axial load. After initial prohlems with surface defects in the wire were cleared up, the incidence of seal leaks was less than 0.1 percent.

Figure 9 shows the results of axial pull tests on 238A-contact seals as compared to 237-contact seals. In this test, the seals are given an initial leak test and then suhjected to an axial load for three minutes. The seal is then given a second leak test. Failure is defined as either complete fracture of the seal or development of a leak greater than 10^{-8} std cc/s. Normally, in lahoratory tests, a helium leak detector is



(a) 200X

(b) 200X

Fig. 6—(a) Remendur reed plated in magnetic rack. (b) Remendur reed plated in nonmagnetic rack.

Fig. 7—Remendur reed plated with hard-gold cross section through a nodule showing magnetic inclusion within the nodule (arrow).

used to check the leak rate. From many measurements like those in Fig. 9, the minimum axial seal strength of the remreed contact has been found to be 111 newtons compared to 40 newtons for the 237B.

The failure mode for the 238A contact when sufficient load is applied is generally complete destruction of the seal, while for the 237B it is development of a high leak rate ($>10^{-6}$ std cc/s) in a visually intact seal at fairly low loads or rupture of the bond between the glass and the 52 alloy shank at higher loads. The 237B failure mode exhibits a time-dependent effect while the 238A failure mode does not. If a 238A contact is going to fail, it happens within the first few seconds of load application. In the case of the 237B, if the load is applied beyond the normal three minutes, additional seals will fail for up to 50 hours.

These differences are not fully understood at the present time, although one possible explanation is that Remendur has a lower creep rate than 52 alloy. Unfortunately, creep data are not available for either material.

There is a second type of seal failure possible for 238A contacts which cannot occur in soft reed contacts. This mode is fracture of the seal due to lateral forces applied to the lead. Since Remendur has a comparatively high yield strength, lateral forces on the lead can be transmitted to the seal. In the case of the soft reed contact, the 52 alloy has such a low yield point that lateral forces on the lead simply

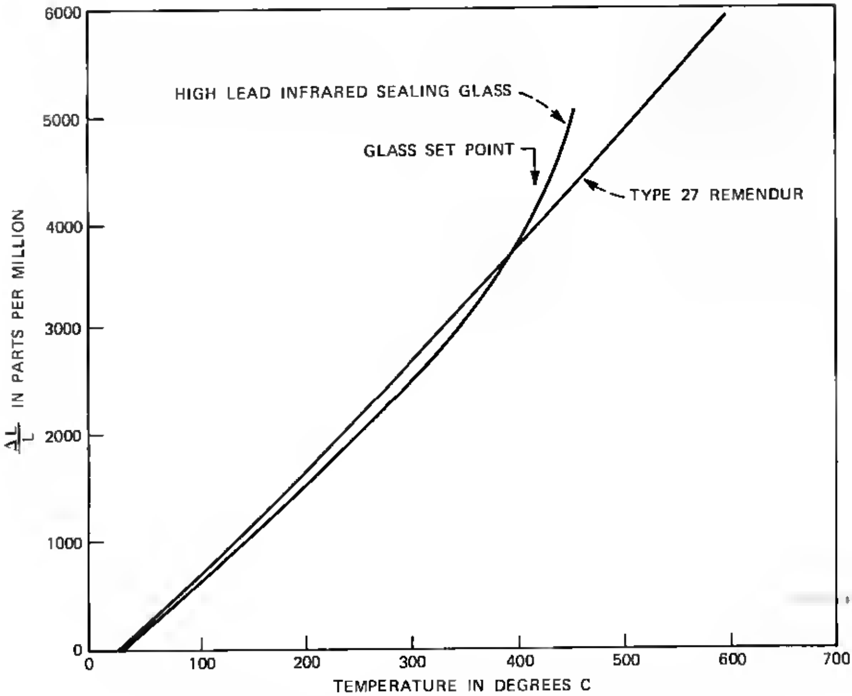


Fig. 8—Expansion curves for Remendur and 52-alloy sealing glass.

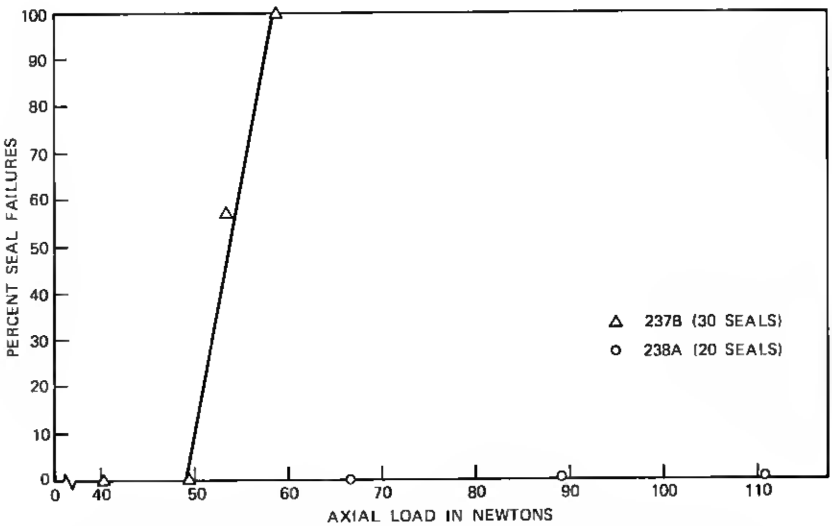


Fig. 9—Comparison of seal strength of 238A and 237B under axial load.

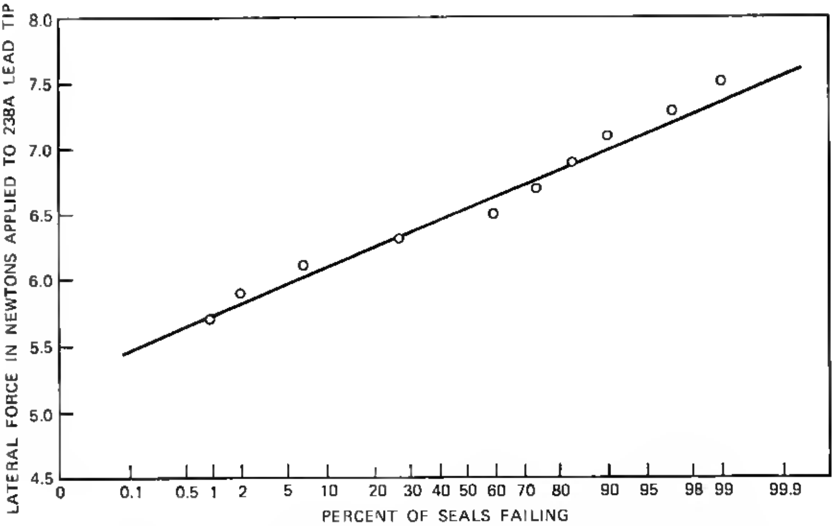


Fig. 10—Distribution of lateral force required to cause 238A seal failures.

result in bending of the lead with very little of the force transmitted to the seal. Figure 10 shows a plot of percent seal fractures versus lateral force applied to the tip of the lead for 238A contacts. Extensive tests of this type have shown that the maximum lateral force which can be applied to the tip of the lead without danger of fracture is 5 newtons.

To avoid seal failure by the above mechanism during switch assembly, a lead concentricity requirement was placed on the 238A contact. This requirement (item I, D, 4 in Table I) assures that the tip of the lead will pass through the associated holes in the flex circuit used in the switch[6] without lateral forces being exerted on the leads.

V. ASSEMBLY

The 238A is assembled on the same machines used to manufacture the 237 contact, with modifications to accommodate the smaller size reeds and glass and to allow for demagnetization of the reeds prior to setting the gap. These are 12-head infrared-type assembly machines. During assembly, the contacts are flushed and filled with a mixture of 97 percent nitrogen and 3 percent hydrogen at a pressure of 2 atmospheres absolute. After cooling, this results in an internal pressure of approximately 1 atmosphere absolute.

One of the most serious problems initially encountered in the manufacture of the 238A contact was severe blistering of the hard gold contact material during the sealing operation. Electrodeposited hard

gold is known to blister when heated above 450°C. It has been assumed that this is due to the breakdown of the codeposited polymer.[7] Rough measurements of the reed tip temperature during sealing, by means of temperature-sensitive paint, showed that it was exceeding 450°C.

At the time the blistering was first observed, an intensive study was made of the effects of plating variables on the blistering temperature.[8] This study showed that the blistering temperature was not a strong function of the plating process. It was concluded at that time that the blistering problem could not be solved by changes in the plating process. What was needed was a reduction of the temperature to which the reed tip was heated during the sealing process.

Studies were carried out to determine if the primary source of heat at the paddle tip was conduction along the reed from the very hot seal area or whether a significant portion of the heat was associated with stray radiation from the infrared sealing lamps. One nonquantitative experiment which indicated that stray radiation was playing an important role was the assembly of contacts using special glass tubes which were coated on the inside with a reflecting material to keep out stray radiation. The hard gold on these special contacts was found to be free of blisters.

As a result of these studies, it was concluded that the blister problem could be completely eliminated by reducing the amount of stray radiation reaching the reed tips. This was accomplished by using a smaller-size infrared lamp with a much shorter filament. The radiation from the shorter filament could be focused into a smaller area.

VI. PHYSICAL DESIGN OF THE 238A

Two significant advantages were obtained in the design of the 238A contact as compared to its predecessor, the 237B: (*i*) a significant miniaturization of the contact—length reduced from 44.96 to 38.05 mm and diameter reduced from 4.32 to 2.79 mm, (*ii*) the inclusion of the magnetic latching elements in the reeds themselves, i.e., replacing 52 alloy with Remendur. The crosspoint volume required for two 238A contacts versus two 237B contacts and their associated Remendur plates is significantly reduced from 2110 to 994 mm^3. The aim of the physical design of the 238A was to obtain this volume reduction with no change in the performance of the contact with respect to the 237B contact. With such a remanent contact design, it was possible to design switch packages so that a complete trunk link network could be built on a 6 ft, 6-in. frame.

The contact parameters which remained to be determined were contact overlap and gap, diameter of wire, reed thickness, plating

thickness, and material properties. The ultimate criteria for judgment of the many contact designs considered was crosspoint performance. In general, minimization of ampere turns necessary for operate and release with ample margin for walkdown effects were the criteria used for judging contact performance.

To measure the relative performance of contacts without laborious measurements in the crosspoint itself, a *B-H* loop is generated for a sealed contact. The coil specifications and the applied magnetic field profile used for the applied drive is shown in Fig. 11.

A typical *B-H* loop is shown in Fig. 12. As the contact is cycled by applying ±250 ampere-turns at a rate of about 100 ampere turns/s, it passes through numerous points of interest. They are defined as follows:

(*i*) Operate field, NI_{op}: that applied field in ampere turns necessary to operate a contact.
(*ii*) Saturate flux, ϕ_s: the absolute value for the flux when $d\phi/dNI$ approaches zero.
(*iii*) Saturate field, NI_s: that applied field in ampere turns to drive ϕ to ϕ_s.
(*iv*) Remanent flux, ϕ_{rem}: the flux measured after the applied field has been cycled through $+NI_s$ to 0.
(*v*) Release field, NI_{rel}: the applied field in ampere turns necessary to cause a saturated contact to open.
(*vi*) Release flux, ϕ_{rel}: the contact flux at the release point, i.e., for NI_{rel} applied field.
(*vii*) Coercive force, NI_c: the applied field in ampere turns necessary to reduce ϕ to zero after saturation.

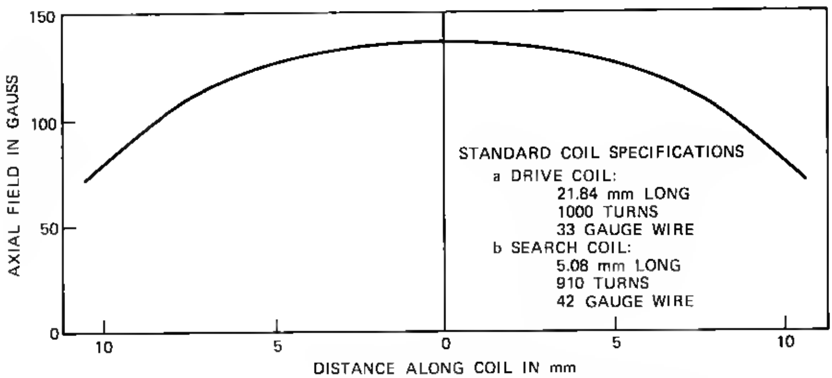


Fig. 11—Field profile and specifications for a standard coil.

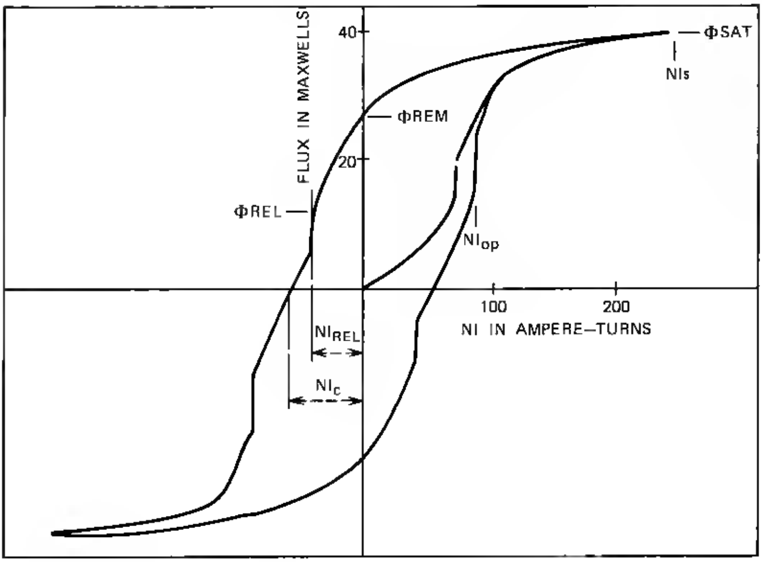


Fig. 12—Typical *B–H* loop.

The points of discontinuity in the *B-H* loop are generated by the reed blades closing and opening. The physical movement of the reeds occurs in a time, $\Delta t \sim 200\ \mu s$, during which the states of magnetization of the reeds change very significantly due to changes in reluctance of the magnetic circuit.

Each sealed contact has a magnetic performance as measured by the *B-H* loop that is dependent on the physical geometry of the contact and the magnetic characteristics of the material. The *B-H* loop data serves a connection between crosspoint characteristics and contact parameters. The contact parameters determine the *B-H* characteristics of a contact design and crosspoint operating characteristics can be related to some of the above defined parameters.

For example, the NI_{rel} value for a sealed contact obtained in a solenoidal coil is directly related to its release value in a crosspoint, while the NI_{op} value determines its susceptibility to false closures, etc. These relationships are covered in more detail in Ref. 6.

Initially, several contact designs were considered, based on variations in the diameter of the Remendur wire. The wire diameters considered were 0.60, 0.53, and 0.51 mm. After these designs were adjusted to have the same operate-and-release characteristics, the 0.53-mm diameter was selected because 0.60-mm wire designs did not provide adequate clearance between reed and glass and 0.51 wire

designs did not generate enough magnetic force. The process of changing contact designs was concurrent witb adjustments in coil design, turns ratio, and magnetic structure in the remreed switch. These adjustments were aimed at obtaining an overall switcb design witb tbe desired features of low currents for actuation and minimum magnetic interference perturbations. The final result involved various compromises between contact and switch design.

Having selected the reed dimensions, the release sensitivity depends on tbe contact geometry through the contact gap, overlap, and the plating thickness of hard gold. The operate ampere turns also depends on tbe gap and overlap, but not the plating thickness.

The relationships among geometry, contact force, release flux, operate flux, and hold flux are well known, having been establisbed by Peek[9] in 1960. However, translation from operate-and-release flux to operate-and-release ampere turns involves the magnetic circuit (including the specific coil geometry) and the exact sbape of the hysteresis loop of the reeds. For this reason, the equations relating contact geometry to operate-and-release ampere-turn values were derived empirically by applying curve-fitting techniques to the data obtained from a series of contacts in which the gap, overlap, and contact-material thickness were systematically varied over the ranges indicated below:

Variable	*Symbol*	*Range*
Gap	X	0.08–0.20 mm
Overlap	a	0.38–1.02 mm
Contact-material thickness	t	0 –3.8 μm

The empirical relationships obtained are:

$$\log (NI_{\text{rel}}) = 1.03 - 0.083t - 0.558 \log X - 0.60 \log(a) \qquad (1)$$

$$NI_{\text{op}} = 78.3 - 7.56a + 285.8X. \qquad (2)$$

These relationships, of course, are only valid over the range of gap, overlap, and contact-material thickness from which they were derived.

Figurcs 13 and 14 were plotted using eq. (1) and show the effects of contact gap, contact overlap, and plating thickness on tbe NI_{rel} value of the contact. Figure 15 was plotted using eq. (2) and sbows the effccts of contact gap on the NI_{op} value of the contact for two different values of overlap.

The magnetic characteristics of the Remendur material determine tbe flux that can be obtained for any applied field; hence, they also have a direct impact on magnetic performance. Unfortunately, eqs.

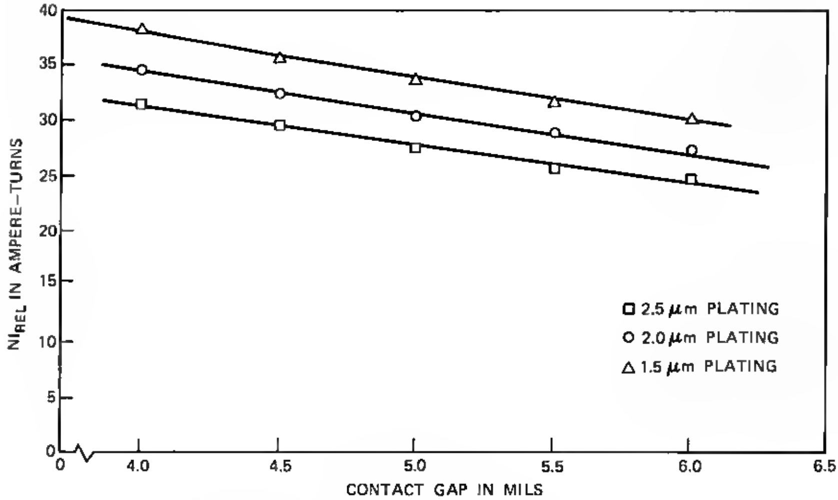


Fig. 13—NI_{rel} versus contact gap, 25-mil overlap.

(1) and (2) are of only limited usefulness, since they do not include the effects of variations in the magnetic properties of the Remendur. Work is currently in progress to derive a set of empirical relationships which will include the properties of the Remendur wire as independent variables.

Other constraints which directly influenced the final contact design were an acceptable range of contact force and a minimum requirement

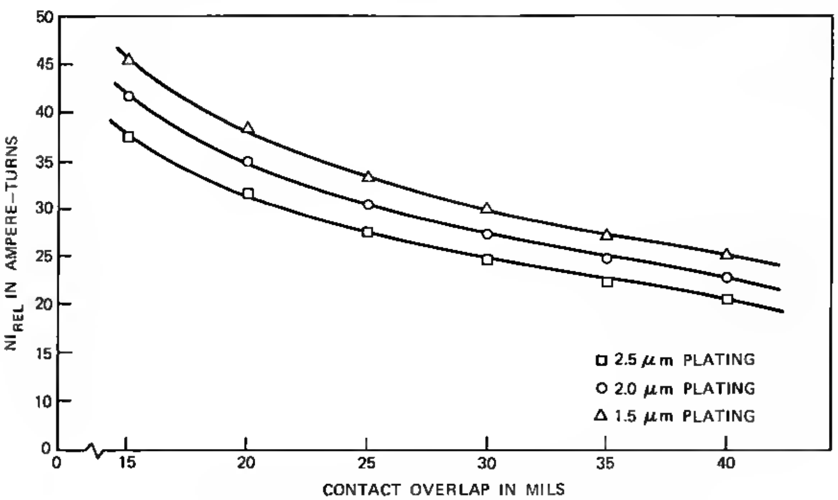


Fig. 14—NI_{rel} versus overlap length, 5-mil gap.

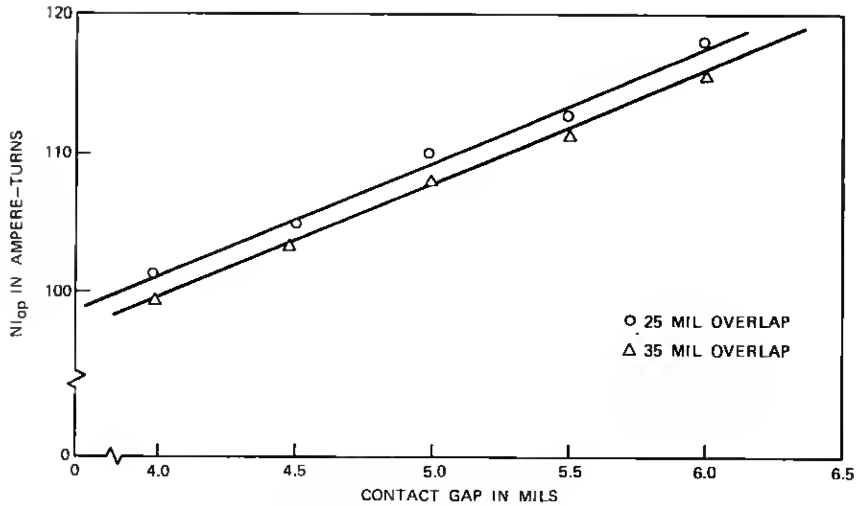


Fig. 15—NI_{op} versus contact gap.

on voltage hreakdown. An estimate of the contact force can he made from geometric measurements and the magnetic test data. The contact force is given hy

$$F_c = \left(\frac{\phi_{\text{rem}}^2}{\phi_{\text{rel}}^2} - 1\right) F_R, \tag{3}$$

where F_R is the mechanical retractile force. F_R is equal to $SX/2$, where S is the stiffness of a single reed and X is the contact gap. S is approximately 32.3 grams/mm for the 238A. The maximum contact force is limited to reduce the incidence of contact sticking, and a minimum force is necessary for stahle contact resistance. This is especially true for stahle dynamic resistance, as explained in the next section. Requirements on the flux ratio control the range of contact force without specific mechanical requirements on overlap, gap, and reed alignment.

The voltage hreakdown constraint, together with the assemhly machine capahility for controlling the gap, fixed the minimum gap that could he considered for the remreed design. As previously stated, remreed packaging constraints limited the overall length of the contact and the diameter of the glass bottle. These size constraints influenced the magnetic circuit hy determining the open gap reluctance via the contact gap and the closed gap reluctance via the effective length-to-diameter ratio.

The actual procedure for precise determination of the contact geometry and the magnetic requirements for the Remendur wire was

related to measured performance of the remreed contact in the remreed crosspoint in the following way. From cross-point studies, requirements on the quasi-static performance of the contact were generated. Nominal values for the contact design parameters, geometry, and material properties were chosen to center the distributions of operate-and-release sensitivities and ratio within the acceptahle range for proper performance. The variations in contact geometry—gap, overlap, and plating thickness—as well as variations in the magnetic properties of the Remendur reeds were estimated hased on experience with outside suppliers of the Remendur wire and with previous experience with the assemhly of the 237B contact. Many contacts were made with worst-case comhinations of the related parameters. The final contact design was chosen so that it would meet the performance constraints, even if all the design parameters deviated from their nominal values in these worst-case combinations.

Thus, a contact design for a specific application, No. 1 ESS, was ohtained which was capahle of heing manufactured with relatively high yields. It also utilized existing facilities and availahle materials.

VII. SEALED CONTACT ELECTRICAL PERFORMANCE

Each 238A contact is given a numher of electrical tests to ensure a uniform and reliable product for application in the remreed switch. Tahle I shows hoth the required electrical characteristics and general design information presently used for remreed contact manufacture. Regarding the electrical characteristics, upper and lower limits are placed on operate and release sensitivities and the ratio of remanence and release flux. The ratio requirement indirectly controls the contact force since the range of retractile forces is relatively small. The operate-and-release requirements protect the remreed switch against defects in contact latching, failures to release, false closures, and false openings. Each contact is tested for voltage hreakdown while in a release state at 800 V dc or 600 V ac with a background radiation of 80 μCi.

One concern with any dry reed sealed contact is sticking of the contact due to adhesion or welding between the mating surfaces. In addition to percussive and resistance welding, which can occur with any contact material under adverse circuit conditions, and mechanical locking of pip and crater late in life even under normal circuit conditions, hard gold is particularly susceptible to cold welding caused hy magnetostrictive scrubbing. "Scruhhing" in the 238A is caused hy the relative movement of the mating surfaces due to magnetostriction when successive operate pulses are applied without separation of the mating surfaces. The contact force during this relative movement of the mating surfaces can vary between 1.3 and 13 grams. The relative

movement of the mating surfaces is ahout 0.5 μm. The probahility of a contact sticking, i.e., failing to release when the magnetic force goes to zero, hecomes significant after five scruhs with virtually all contacts sticking after 1000 scrubs.

Figure 16 shows the numher of failures to release as a function of the numher of scruhs for some standard contacts in remreed switches.

To eliminate scruh sticking in the remreed switch, an additional control pulse (the prerelease pulse) was added 7.2 ms before the operate pulse[6] to ensure that the contact would open between successive operate pulses. This prerelease pulse prevents scruhhing of the contact surfaces. Life test data[10] indicate that sticking due to other causes will he at an acceptahle level.

To avoid scruh sticking, the time-to-release for contacts therefore must he less than 7 ms, since the prerelease pulse is 7.2 ms hefore the

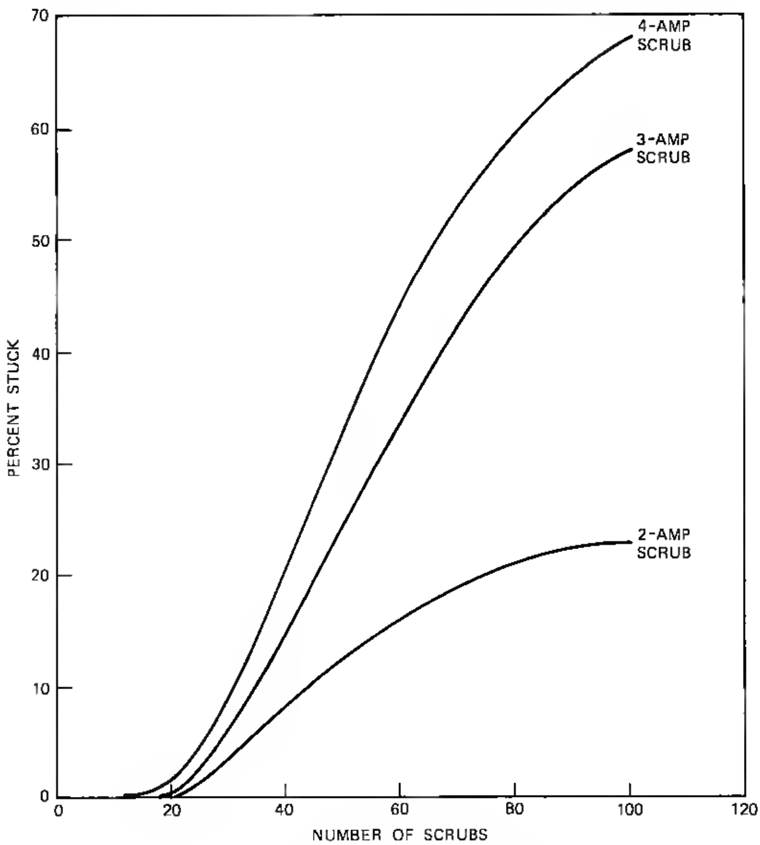


Fig. 16—Remreed scrub sticking.

operate pulse in the ESS application. Data given in Table I show that the mean release time plus three sigma is about 200 μs for the 1-ms release pulse of 4 amperes amplitude used for prerelease in a remreed cross-point. With such ample margin, it is not necessary to test contacts for this characteristic.

A second failure mode is high resistance due either to contamination or wear-through of the thin, hard gold contact layer. Life tests have indicated that, under ESS circuit conditions, this failure mode is also at an acceptable level.[10] The evaluation of the reliability of the 238A is more fully discussed in Ref. 10.

A static resistance test was, from past experience with the 237B soft reed contact, perceived to be of value for eliminating contacts that would cause contact resistance failures in remreed switches. After the introduction of the prerelease pulse to the operate pulse sequence in the remreed crosspoint, the level and the durations of dynamic resistance increased. Some factors which contribute to the tendencies of contacts to have high dynamic resistance are: contamination of the contact surfaces, low contact force, natural frequency differences between reeds, the pulse shape used for operation of the contacts, and the interpulse time between the prerelease pulse and the operate pulse.[6] To eliminate contacts with these transient high-resistance characteristics, a dynamic-resistance test which closely simulates the operation of the contact in the crosspoint was developed.

Therefore, a sequence of dynamic- and static-resistance tests are applied to each contact to control the incidence of contamination of the contact surfaces and abnormal dynamic resistance. If the static contact resistance exceeds 90 milliohms after closure by a 250 NI soak field, or if the peak dynamic resistance exceeds 150 milliohms after application of a 150 NI pulse, the contact is rejected.

VIII. SUMMARY

A new contact in the family of sealed contacts, the 238A, has been successfully developed for application in ESS. A semihard magnetic material, Remendur, is used as the reed material to provide the residual holding force for latched operation. The mating surfaces of the contacts are hard gold, which is electroplated on the reed tips.

The impetus for this contact development hinged on the solution of three major problems in sealed contact manufacture: (*i*) processing of the Remendur into reeds; (*ii*) electroplating of a suitable precious metal on the reeds; and (*iii*) making a secure glass-to-metal seal. The physical design and magnetic material selection for magnetic properties was based on the required performance of the remreed crosspoint and the use of commercially available material. A testing scheme

which reduces switch failures while allowing good contact yield has evolved and is still heing perfected.

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